

Columbia University
in the City of New York

HUDSON LABORATORIES
DOBBS FERRY, N.Y.



Technical Report

No. 73

**A Detailed Investigation
Of the Absorption by Water
Of Electromagnetic Radiation**

by

B. P. Fabricand

AUGUST 15, 1957

Contract

N6-ONR-27135

GC
661
.F3
1957

cription by
By B. P.
dson Labs.

RE-RETURNED

1 1960

Renewed

*Renewed
4 dec 1978*

DEMCO

MBL/WHOI



0 0301 0032704 5

Columbia University
Hudson Laboratories
Dobbs Ferry, N.Y.

R. A. Frosch
Director

Technical Report No. 73

A DETAILED INVESTIGATION OF THE ABSORPTION
BY WATER OF ELECTROMAGNETIC RADIATION

by

B. P. Fabricand

August 15, 1957

This report
consists of 19 pages

Copy No. 24
of 65 copies

Research Sponsored by
Office of Naval Research
Contract N6-ONR-27135

Further distribution of this report, or of an abstract or reproductions, may be made only with the approval of Chief of Naval Research (Code 466). Reproduction in whole or in part is permitted for any purpose of the United States government.

ABSTRACT

The various mechanisms for the absorption and scattering of electromagnetic radiation in sea water have been examined with the idea of evaluating the possibilities of windows anywhere in the spectrum. It is concluded that the chances of finding a window are negligible except of course for the one in the visible region which however is rather cloudy.

TABLE OF CONTENTS

Introduction	1
Absorption Processes at Very High Frequencies	1
Pair Production and Compton Effect ($\geq 10^{18}$ cycles/sec)	1
The Photoelectric Effect ($\geq 3 \times 10^{15}$ cps)	3
Absorption Processes in the Visible Region	4
Scattering of Light by Na^+ and Cl^- ions (Thomson scattering)	4
Scattering by Small Particles	4
Molecular Scattering	6
Absorption and Dispersion for Ultra-Violet and Infrared Frequencies	6
Absorption at Longer Wavelengths (D. C. to Microwave)	8
Experimental Results	10
Discussion	13

Introduction

The main purpose of this report is to examine the theoretical and experimental evidence which exists on the absorption of electromagnetic radiation by water in the hope of finding windows through which the radiation may propagate with little attenuation.

There were two principal reasons for reopening this subject:

- 1) In the last two or three years, there have been great advances made in the detection of radiation, especially in the infrared region of the spectrum;
- 2) There does not seem to be any adequate investigation of water absorption in the infrared using modern techniques.

There have been measurements covering various ranges of frequency, and these will be reviewed below. Furthermore, the reasons for the known great absorption in the infrared do not appear to be adequately explained on a theoretical basis.

The term absorption will also include any scattering process by which a beam of radiation is attenuated. There are a number of mechanisms of absorption, and each will be considered in the next sections. Following this, a review of the experimental work on absorption in water will be presented. A summary of absorption throughout the whole spectrum will be given in the next section; and in the final section of this report, a discussion and recommendations for any future work will be made.

The Absorption Processes at Very High Frequencies

The processes will be considered roughly as a function of the frequency at which a specific process is most effective, starting with the highest frequencies.

A. Pair Production and Compton Effect ($\geq 10^{18}$ cycles/sec)

These processes are effective only at extremely high frequencies, in the region of the spectrum usually referred to as gamma rays (10^{18} cps and up). Absorption by pair production arises when a gamma ray disappears and gives rise to the creation of a positron and an electron. This process must take place near a nucleus in order to conserve momentum. The Compton effect arises from the scattering by electrons of the electromagnetic radiation.

The intensity I of a monochromatic beam passing through water decreases exponentially according to

$$I = I_0 e^{-\alpha x}$$

where I_0 is the initial intensity, x the depth of penetration, and α the absorption coefficient. α is composed additively of a part due to pair production and a part due to the Compton effect:

$$\alpha = \alpha_{\text{pair}} + \alpha_{\text{compt.}}$$

If σ represents the cross-section of one atom for one of these processes, the corresponding α is given by

$$\alpha = N\sigma$$

where N is the number of atoms per cm^3 . The cross-sections for these processes are given in the book by Heitler¹ and will not be reproduced here. The expression for σ_{compt} is considered exact, although errors arise in σ_{pair} from screening by atomic electrons and use of the Born approximation. However, these errors are negligible for the present purpose. Since σ (and α) are independent of any molecular and atomic interactions in the medium, a theoretical calculation of absorption from these two processes will be extremely accurate.

Table I is taken from Heitler and gives α per cm for various frequencies, these being expressed in units of the rest energy of the electron.

TABLE I. ABSORPTION OF GAMMA RAYS IN H_2O

$\frac{h\nu}{mc^2}$	.1	.5	1	2	5	10	20	50	100	1000	10000
ν	1.2×10^{18}	6×10^{18}	1.2×10^{19}	2.4×10^{19}	6×10^{19}	1.2×10^{20}	2.4×10^{20}	6×10^{20}	1.2×10^{21}	1.2×10^{22}	1.2×10^{23}
α	.186	.124	.095	.069	.043	.030	.022	.016	.015	.0165	.017

It can be seen from Table I that the absorption decreases with frequency up to $\frac{h\nu}{mc^2} = 100$ and then starts increasing again. The fall-off results from a decrease in Compton scattering with frequency, while the rise results from the creation of pairs.

The absorption continues to increase with frequency and finally tends to a constant asymptotic value. The maximum mean free path for the radiation (the path length needed to decrease the intensity to 1/e of its initial value) occurs at $\frac{h\nu}{2mc} = 100$ and equals $1/\alpha = 67$ cm. Thus, it can be seen that there is no hope of finding a window at any frequency interval above 10^{18} cps. Furthermore, it will be shown in the next subsection on the photoelectric effect that this lower limit can be extended to about 10^{15} cps.

B. The Photoelectric Effect ($> 3 \times 10^{15}$ cps)

The photoelectric effect arises when an electron in an atom or molecule absorbs a photon from incident radiation and makes a transition to the continuum, becoming a free particle. This effect, then, is effective at photon energies greater than the ionization energy of the atom or molecule, and the absorption spectrum is continuous.

For the calculation, the absorption due to water will be approximated by that of hydrogen. The ionization energy of water is 12.56 volts and that of hydrogen 13.6 volts, so that the absorption per molecule or atom is nearly the same. For frequencies much larger than the ionization frequency of the atom, the absorption coefficient is¹

$$\alpha = N \Phi_0 \frac{Z^5}{(137)^4} 4\sqrt{2} \left(\frac{mc^2}{h\nu} \right)^{7/2}$$

where N is the number of atoms per cm^3 , Z the nuclear charge, Φ_0 the Thomson scattering cross-section. For hydrogen in water, Table II gives values of α as a function of frequency.

TABLE II. ABSORPTION OF GAMMA RAYS BY HYDROGEN
(photoelectric effect)

λ Å	.1	1	10	20	40	80	800
$\frac{h\nu}{mc^2}$	.24	.024	.0024	.0012	.0006	.0003	.00003
α	5×10^{-8}	.00016	.5	5.5	60	720	180000

It is seen that the absorption falls off sharply with increasing frequency ($\nu^{7/2}$ from the formula), until it reaches the very small value of 5×10^{-8} per cm at $\frac{h\nu}{2mc} = .1$. However, Table I shows that in this frequency range the Compton effect is very appreciable and rising with decreasing frequency so that there is little penetration by the radiation.

Furthermore, there will be a great deal more absorption from the other elements present in water, notably oxygen and nitrogen.

It can be seen, therefore, from this and the preceding section, that there is no hope of finding a window at any frequency higher than the ionization frequency of water ($\sim 3 \times 10^{15}$ cps = 1100 Å). At frequencies below this, the photoelectric effect disappears. The rest of the report will be concerned with this lower frequency region.

Absorption Processes in the Visible Region

A. Scattering of light by Na^+ and Cl^- ions (Thomson scattering)

When light falls on free charged particles, it sets them into oscillation and causes them to emit radiation. The cross section for this process¹ is

$$\sigma = \frac{8\pi}{3} \left(\frac{e^2}{mc^2} \right)^2.$$

For Na^+ and Cl^- , σ is 3.3×10^{-33} cm² and 1.5×10^{-34} cm² respectively. The mean free path of the radiation for this process $\lambda = \frac{1}{n\sigma}$ (where n is the ion concentration, here the NaCl concentration in the ocean, 3.6×10^{19}) is

$$\lambda = \frac{1}{3.6 \times 10^{19} (1.5 + 3.3) \times 10^{-34}} \cong 10^{13} \text{ cm.}$$

Therefore, any absorption of the incident radiation due to this process is negligible. If, as is probable, the Na^+ ion forms a complex in water, the effect will be even less.

B. Scattering by Small Particles

² The scattering of light by small particles has been discussed by Mie,³ Bom,³ and Stratton.⁴ The mathematics involved is lengthy and laborious, and only an indication of what goes on will be sketched here. Some experimental results will be presented below.

The simplest model is that of a small sphere upon which is incident a plane electromagnetic wave. To describe the scattering, solutions of Maxwell's equations must be found that add up to give a plane wave at large distances from the sphere, and also are of the proper form to satisfy boundary conditions at the surface of the sphere. It turns out that the scattering cross section can be represented by a series of functions which depend on the dielectric constant and conductivity of the sphere, and the ratio, a/λ , of sphere radius to wavelength. The first term of the series is seen to be the radiation emitted by an electric dipole, while the other terms correspond to emission by higher multipoles.

As an example, the back scattering cross-section of a sphere of dielectric constant ϵ and infinite conductivity for $a/\lambda \ll 1$ is given by only the dipole term

$$\frac{\sigma}{\pi a^2} = 1.4 \left(\frac{a}{\lambda} \right)^4 \times 10^4.$$

It is seen that this is the famous Rayleigh scattering which accounts for the blue color of the sky.

Fig. 1 shows a plot of this cross-section vs a/λ .

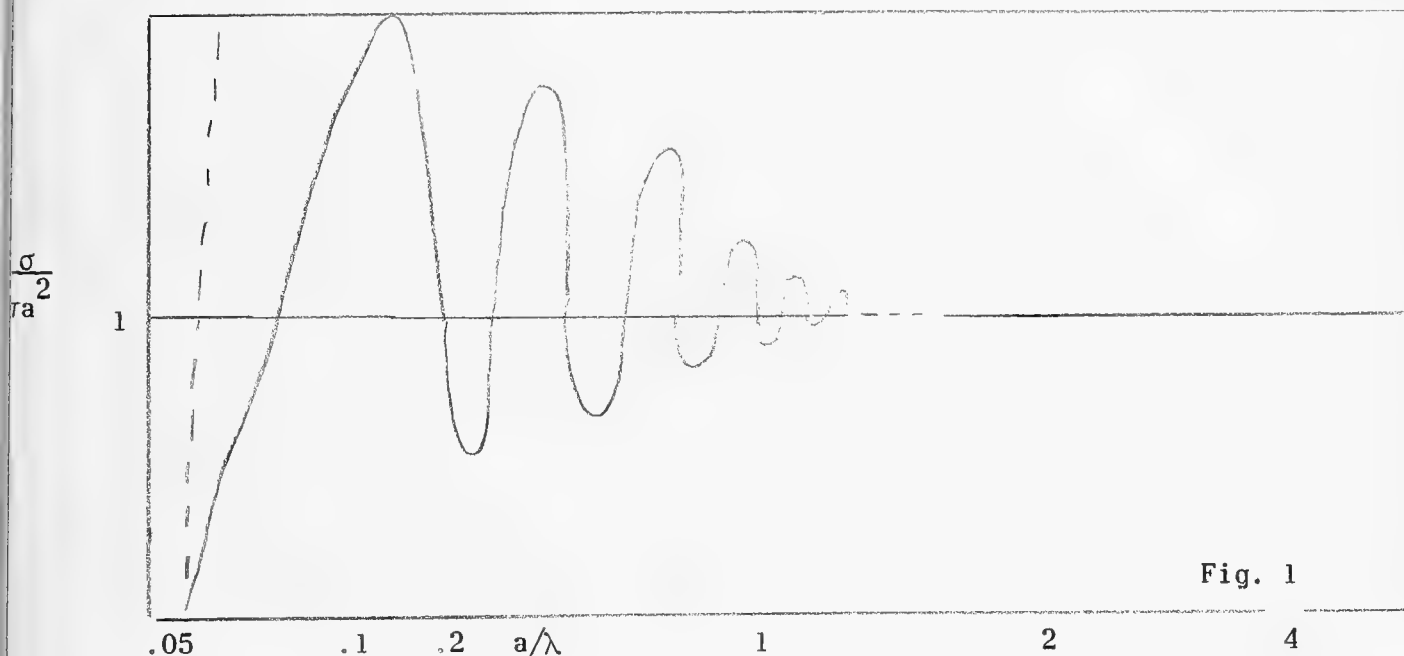


Fig. 1

The $\left(\frac{a}{\lambda} \right)^4$ or Rayleigh scattering is shown by the dotted line. It coincides with the solid curve for $a/\lambda \ll 1$. At about $a/\lambda = .05$, higher order multi-pole terms become larger and fluctuate in phase and magnitude causing the oscillations. As a/λ becomes larger, σ approaches the geometrical cross-section.

As a sample calculation, suppose water containing one part per million by volume of infinitely conducting spheres scatter radiation of wavelength 6000 Å (visible region). For radii of 12000 Å ($\sim 10^{-4}$ cm) the scattering cross-section is about geometric, πa^2 . The mean free path for this radius is given by $1/n \pi a^2$ where n is the number of scattering particles per cubic centimeter (2.5×10^5 in this case). Its value is 130 cm. Experimental results pertaining to the clarity of ocean water will be discussed below.

C. Molecular Scattering

From the microscopic point of view, an electromagnetic wave incident on a substance distorts the molecules of the substance, thereby inducing molecular dipole moments. These induced dipoles can be considered as vibrating in a vacuum. They radiate 1) a wave which exactly cancels the incident wave in the substance, 2) a reflected wave, 3) a refracted wave, and 4) a scattered wave. The details of this process are presented in the book by Born. It is shown there that the first three processes depend only on the average induced dipole moment per unit volume, while the fourth process depends on deviations from this average moment such as would be produced by density fluctuations.

The intensity of the scattered radiation J is

$$J = 4\pi \frac{(2\pi)^4}{\lambda^4} p^2 \overline{(\Delta N)^2}$$
$$= 4\pi \frac{(2\pi)^4}{\lambda^4} \frac{1}{m} p^2 kT\rho K$$

where p is the induced dipole moment, ΔN is the fluctuation in the number of molecules per unit volume from the average value, ρ the density, K the compressibility. It depends on the inverse fourth power of the wavelength as in the case of scattering by particles. However, this scattering occurs in the purest substances.

The cross section is obtained by dividing J by $CE^2/4\pi$:

$$\sigma = \frac{256\pi^6}{c\lambda^4} \frac{1}{m} \alpha kT\rho K,$$

since $p = \alpha E$, where α is the polarizability of the molecule and E the incident field. For radiation of wavelength 6000 Å incident on water at 20°C,

$$\sigma \sim 7 \times 10^{-28} K = 3.5 \times 10^{-38}.$$

The radiation mean free path is $\frac{1}{n\sigma} = 10^{15}$ cm, so that this effect is negligible.

At the triple point of water, $T = .0075^\circ\text{C}$ and $p = 4.58$ mm, K becomes extremely large and water becomes practically opaque.

Absorption and Dispersion for Ultra-Violet and Infrared Frequencies

Up to this point of the report, scattering processes have been considered (except for the high energy processes of photoelectric absorption and pair production). This section will be concerned with the absorption and dispersion (the variation of the index of refraction with frequency) of radiation. Very general relations exist between the refractive index and the absorption coefficient that enable one to determine the absorption if

the dependence of the refraction index on the frequency is known throughout the spectrum from $V = 0$ to $V = \infty$ and vice versa. These relations arise from a correlation of these two quantities with the real and imaginary parts of a complex dielectric constant, as first noted by Kramers⁵.

The relations⁶ are as follows if the dielectric constant $k = k_1 + ik_2$:

$$k_1(v) - k_\infty = \frac{2}{\pi} \int_0^\infty \frac{v' k_2(v')}{v'^2 - v^2} dv'$$

$$k_2(v) = - \frac{2}{\pi} v \int_0^\infty \frac{k_1(v') - k_\infty}{v'^2 - v^2} dv'.$$

These relations are very general, assuming only the law of cause and effect. Their validity is general and irrespective of the model, which can be either classical or quantum-mechanical. The structural unit can be an atom, electron, molecule, water drop, etc., provided only that a considerable number of them be included in a volume unit whose dimensions are small compared to a wavelength. Qualitatively, the relations state that any change in refractive index is accompanied by absorption of the radiation.

There are two large regions of the spectrum over which the index of refraction changes appreciably: 1) the region between X-rays and the visible; and 2) that between the visible and the radio-frequency part. In these two regions, therefore, great absorption is to be expected. However, this does not preclude the existence of windows in these frequency regions.

The visible region of the spectrum has been discussed above and will be considered below from an experimental viewpoint. Obviously, a window does exist here; the question is how much of one. The region from d. c. to radio-frequency will also be considered below, although at these frequencies the conductivity of water contributes to a large absorption. Ultra-violet and infrared absorption will be considered in the rest of this section.

In common with other molecules possessing a dipole moment, water molecules exhibit an infrared absorption spectrum.⁷ This spectrum arises from the rotational and vibrational degrees of freedom of the molecule; a quantum of radiation induces a transition from one rotational and/or vibrational state to another, being absorbed in the process. The resulting spectrum is quite complicated owing to the fact that water is an asymmetric top molecule, i.e., one that has three different principal moments of inertia. Quantitative formulae for the representation of the rotational energy levels are given in Herzberg's book⁷. The levels for an asymmetric top molecule

fall somewhere in between the levels for a prolate and oblate symmetric top molecule. To each value of the total angular momentum J of the molecule, there are $2J+1$ levels which arise because there are components of the total angular momentum about the figure axis of the molecule. The rotational spectrum resulting from transitions between the levels is complicated and extends throughout the infrared. It is shown in Herzberg's book for water vapor. Although extensive, there are numerous windows in the vapor. However, the situation in the condensed or liquid state is far from clear. It would seem that in the liquid, the molecules are not freely rotating, but are in hindered rotational or torsional oscillating states. Debye⁸ bases his theory of non-resonant dispersion in water on the assumption that the rotations of the molecules are opposed by a viscous force. Bernal and Fowler⁹ believe that about $1/6$ of the molecules are able to rotate freely, while Pople¹⁰ considers the molecules as undergoing at most torsional oscillations. In any event the rotational absorption lines will certainly be smeared out in the liquid, although the smearing should be less the higher the frequency. The question of a window would have to be decided on experimental grounds because of the uncertain nature of the liquid. This question will be discussed further below.

The vibration modes also contribute to infrared absorption, and, to some extent, absorption in the visible region of the spectrum. There are three normal modes of vibration possible for a water molecule; and for each mode there exists a set of vibrational states. Since the spacing between states decreases with increasing vibrational quantum number, transitions between states give rise to the well-known absorption bands. For the water molecule, the three main bands corresponding to the three normal modes occur at 6.3, 2.66, and 2.74 microns. In addition, other bands arise because of the anharmonicity of the vibrations--overtone and combination vibrations occur, which, however, will be much weaker than the fundamentals since the anharmonicities are usually small. These bands extend well into the visible spectrum and are tabulated in Herzberg's book. In the liquid the fundamental bands occur at about the same frequency as in the vapor. This is to be expected because of the very short period of the vibrations compared to any reasonable estimate of collision times in the liquid. There also appear new bands in the same region of the spectrum which are attributed to molecular association. Absorption graphs will be shown below.

At the high frequency side of the window, absorption results from the electronic structure of the molecule. Like many molecules water possesses a continuous absorption band in the blue ultra-violet. These electronic transitions are not affected very much in the liquid state except that there is a shift of the band maximum to higher frequencies. It will be seen below that absorption reaches a minimum in the visible and starts up sharply on either side.

Absorption at Longer Wavelengths (D.C. to Microwave)

At frequencies lower than infrared, the conductivity of water, most of which arises from ions of sodium and chlorine, contributes to absorption of radiation. This can be seen as follows: For a conducting medium, the

wave equation is

$$\nabla^2 \ddot{\vec{E}} = \frac{\epsilon}{c^2} \ddot{\vec{E}} + \frac{4\pi\sigma}{c} \dot{\vec{E}}$$

which reduces to

$$k^2 = \frac{\epsilon\omega^2}{c^2} - \frac{4\pi\sigma\omega}{2} i .$$

ϵ is the dielectric constant, and σ the conductivity. Since $E \sim e^{ikx}$, it can be seen that the imaginary part of k^2 contributes an absorption term to E . The conductivity $\sigma = ne\mu$ where n is the ion density and μ the ion mobility. For high frequencies (infrared and higher), the mobility of heavy ions like Na^+ is approximately zero. At lower frequencies, the ions can follow the changes in electric field and thus move. The resulting collisions are taken into account in a macroscopic way by putting in the free space wave equation a damping term proportional to \dot{E} . This is the term which leads to absorption.

An idea of the dependence of the amplitude of motion of the ions on frequency and intensity can be gained from the following. The equation of motion of a free ion is

$$e E = m \ddot{r}$$

and the amplitude of its motion is

$$r = \frac{e}{m\omega^2} E .$$

The following table gives some numbers based on $E = .024$ e.s.u. (the value for sunlight).

r_{cm}	λ (Angstroms)
1.3×10^{-20}	5000
5.2×10^{-20}	10000
5.2×10^{-18}	100000
5.2×10^{-16}	10^6 (.01 cm)
5.2×10^{-12}	10^8 (1 cm, 30,000 mc)
5.2×10^{-8}	10^{10} (300 mc)
5.2×10^{-4}	10^{12} (3 mc)

A rough value of the mean free path of sodium and chlorine ions in solution may be obtained from the diffusion constant for .2N NaCl

in water which is $D = 10^{-5} \frac{\text{cm}^2}{\text{sec}}$. The mean free path $l = 3D/v \approx 10^{-9} \text{cm}$, assuming a velocity of a free ion in vacuum at room temperature ($2.7 \times 10^4 \text{cm/sec}$). Thus it can be seen that there will be no absorption from the ions until the region between the infrared and microwaves is reached, and even here, the amount of absorption depends on the amplitude of the electric field. However, in this intermediate region (about 1 cm) there is great absorption from other effects. There is a very broad water absorption line at 1.35 cm, and one due to oxygen (whose concentration in water is about 1/10 that in air) at 1/2 cm arising from its electronic magnetic moment. For wavelengths longer than 1 cm, the absorption falls off enough to permit effective use of radar in air at 10 cm. But in water, the skin effect, which arises from the ions, becomes of importance and drastically limits propagation.

For low frequencies ($\frac{\sigma^2}{\epsilon \omega^2} \gg 1$), the absorption factor $\alpha = \sqrt{\frac{\omega \sigma}{2}}$.

This term is responsible for the well-known skin effect. At 1 mc/sec, α is about .1 for sea water, giving a mean free path of 10 cm. It is easily seen that propagation of these frequencies is not feasible except perhaps at the lowest ones, and here there are immense problems of efficiency in radiating and receiving equipment. Furthermore, wavelengths in this region are so long that scattering from any object the size of a submarine is apt to be extremely small because of the $1/\lambda^4$ dependence (see above). Low radio frequencies ($\lambda > 30 \text{ cm}$) show little attenuation and have been used in practice. The English station Rugby used 16 kc/sec to transmit to a submarine with an antenna 30 feet underwater at ranges up to 3000 miles.

Experimental Results

In this section will be presented a brief survey of experimental work measuring absorption in the visible and infrared.

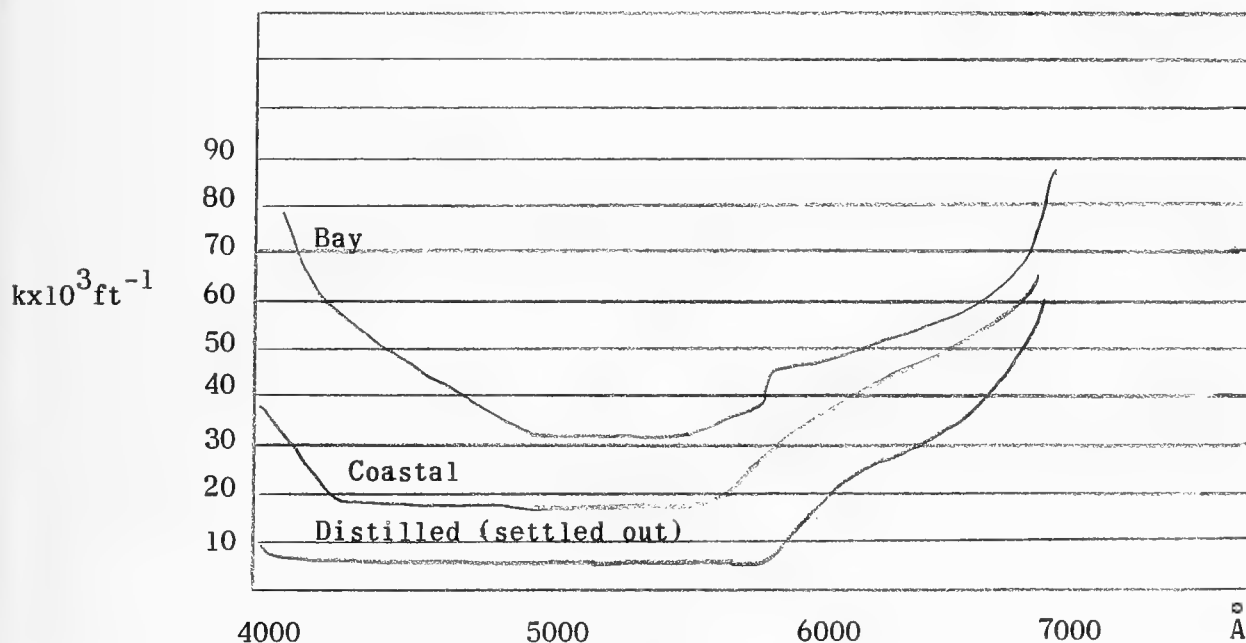
Clarke and Backus¹¹ measured a light intensity of $10^{-11} \text{ watt/cm}^2$ at a depth of 550 meters when there was a surface intensity of .05 watts/cm². This experiment took place on July 20, 1955, about 200 miles southeast of New York City. The measurements correspond to an attenuation of .0125 or a mean free path of about 80 feet. These measurements agreed with those of Hulbert¹² who measured the absorption and scattering of light in distilled water, Chesapeake Bay, and coastal waters off Hollywood, Florida. Some of his results are reproduced here:

Distilled Water

Chesapeake Bay

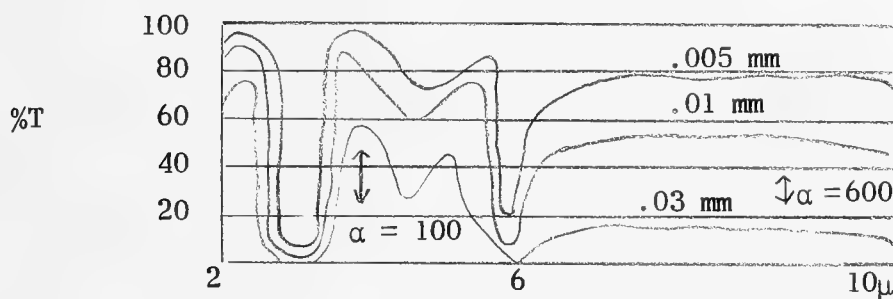
$\frac{\lambda}{\text{\AA}}$	$\frac{\sigma}{\text{cm}^{-1}}$	$\frac{\beta}{\text{cm}^{-1}}$	$\frac{\sigma}{\text{cm}^{-1}}$	$\frac{\beta}{\text{cm}^{-1}}$
4000	3.6×10^{-3}	4.4×10^{-3}		
4500	2.25	1.7	19	37
5000	1.5	2.3	17	21
5500	1	3.7	18	14
6000	.7	19	18	25
6500	.5	30	18	34
7000	.4	57	18	56

σ is the part of the absorption of a light beam arising from scattering and β that due to pure absorption. The total absorption is given by $k = \sigma + \beta$ where k occurs in the exponential e^{-kx} . Hulbert also exhibits the following graph:

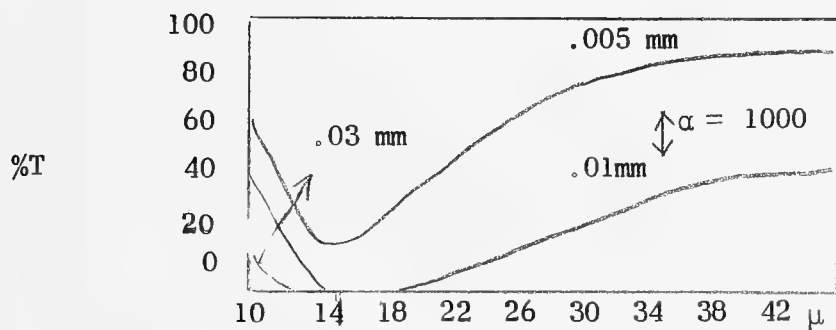


By comparing Hulbert's work with that of Burt¹³, it may be seen how very pure ocean water is. Burt measured extinction of light in Chesapeake Bay caused by suspended particles. He concluded that particle concentration ranges from 1 to 60 parts per million by volume and that the average particle radius is 6×10^{-5} cm. Since coastal water is much less absorbing than bay water, it may be concluded that it is very dust free and contains much less than the 1 part per million of suspended particles than was used in the example of the section, Absorption Processes at Very High Frequencies.

The best measurements of infrared absorption seem to be those of Plyler and Acquista¹⁴ whose results are graphed below. These authors used a Perkin-Elmer double beam spectrometer and three different sample thicknesses of water.



liq H₂O



The graphs plot the percentage transmission against wavelength in microns. The numbers on the graphs give the sample thicknesses. α gives the approximate absorption coefficient at the specified wavelength in cm^{-1} .

Cartwright¹⁵ states that there is a gradual increase in T from 50 to 150 microns.

The following experiment was carried out in the Hudson Laboratories by the author to investigate the infrared in a manner more suitable for the discovery of a window. Infrared absorption experiments invariably use a beam of narrow frequency range to obtain the highest resolution. Therefore, it is possible that although there may be some penetration in this narrow band, it may be too small to detect. Furthermore, the region of wavelength greater than 50 microns does not seem to be adequately covered.

The experiment was done in such a way that contributions from any window in the entire infrared, no matter how small, would add up in the detector to give a response. A "Glo-bar" source furnished a black body spectrum throughout the infrared. The radiation was then passed into water contained in an aluminum tray, was reflected from the bottom of the tray and into an Eppley thermopile which served as a detector. A germanium filter was used over the detector to cut out any radiation of wavelength shorter than 1.8 microns, especially the visible which begins at about .75 micron. The sensitivity of the system was such that a microwatt per square centimeter of radiation could have been detected. However, 1/2 inch of water was more than enough to stop any radiation whatsoever from reaching the detector. The question of whether or not a more sensitive detector would be worthwhile will be gone into in the next section.

Discussion

Gathering together all the theoretical and experimental results presented above, the following pertinent facts stand out:

- 1) There is no hope of finding a window at wavelengths of 3500 \AA and shorter. This result is based on the absorptions due to pair production, Compton effect, photoelectric effect, and molecular electronic transitions.
- 2) A window does exist in the visible. However, the radiation mean free path of about 80 feet precludes any use of these frequencies for detection at distances greater than a mile, and even this is stretching the point.
- 3) There does not seem to be any window in the infrared. This conclusion is based mainly on the work done at Hudson Laboratories. As mentioned above, there remains the question as to whether or not a more sensitive detector should be employed. This question will be considered below along with possible reasons for the lack of a window in the infrared.
- 4) The region from the very far infrared to D. C. is adequately covered by standard electromagnetic theory. The only possible window is at very low frequencies where the skin depth approaches distances of interest. However, equipment difficulties in this region seem insuperable at the present time. Thus, it would appear that the use of electromagnetic radiation for detection in sea water is out of the question. As remarked by D. Sternberg¹⁶, "Evolution is against us."

There remains the question of why there is no window in the infrared for water when many windows exist for the vapor. Obviously, the reason is connected with the much closer association of molecules in water. Two explanations have presented themselves:

1) With the close association of molecules, there arise clusters which have a great number of possible modes of vibration. For each mode there exists a frequency spectrum in a different frequency range. It's quite possible that there are enough different size clusters to completely cover the infrared region.

2) As mentioned above, water vapor has a rotational spectrum spread out through the infrared. In the liquid it is probable that there is no free rotation for the water molecule, but only hindered rotation. Whether free or hindered, however, each rotational state will be split by any electric field present, the amount of splitting depending on the strength of the field. Because of the fact that water possesses a dipole moment of 1.87 Debye, rather strong fields exist at each water molecule. An estimate of this field can be obtained from the formula

$$E \sim \frac{\mu}{r^3} = 1.87 \times 10^{-18} / (2 \times 10^{-8})^3 = 2.5 \times 10^5 \text{ e.s.u.}$$

or about 10^8 volts/cm. This huge field depends critically on the positions of neighboring molecules and therefore fluctuates considerably. In effect the fluctuation smears out each rotational level and could well account for the lack of a window.

It seems to the author that these two reasons are extremely strong arguments against the purchase of additional and much more expensive infrared detectors of greater sensitivity than the Eppley thermopile. Some work remains to be done in this field dealing with the problems of the effect of association of molecules on radiation and the measuring of the electric fields present in water. However, these topics will be covered in a future report.

REFERENCES

1. The Quantum Theory of Radiation, W. Heitler.
2. Mie, Ann. Physik 25, 377 (1908).
3. Optik, M. Born.
4. Electromagnetic Theory, J. Stratton.
5. H. A. Kramers, Como 2, 545 (1927).
6. For a detailed discussion, see RL Report No. 735 by J. H. Van Vleck.
7. Infrared and Raman Spectra, G. Herzberg.
8. Polar Molecules, P. Debye.
9. Bernal and Fowler, J. Chem. Phys. 1, 515 (1933).
10. J.A. Pople, Proc. Roy. Soc., London, 205A, 163 (1951).
11. Clarke and Backus, Deep-Sea Research 4, 1 (1956).
12. Hulbert, J. Opt. Soc. 35, 698 (1945).
13. Burt, J. of Marine Res. 14, (1955).
14. Plyler and Acquista, J. Opt. Soc. Am. 44, 505 (1954).
15. Cartwright, Nature, 135 and 136 (1935).
16. Private conversation.

D I S T R I B U T I O N

Office of Naval Research (Code 466)
Navy Department
Washington 25, D. C.
copies 1-2

Director
Naval Research Laboratory
Washington 20, D. C.
Attn: Code 5500, Dr. H. L. Saxton
copies 17-18

Commanding Officer and Director
U. S. Navy Underwater Sound Laboratory
Fort Trumbull
New London, Connecticut
copies 3-4

Commanding Officer and Director
U. S. Naval Electronics Laboratory
Point Loma
San Diego 52, California
copies 19-20

Director
U. S. Naval Ordnance Laboratory
White Oak
Silver Springs 19, Maryland
copies 5-6

Commander
U. S. Naval Air Development Center
Johnsville, Pennsylvania
copies 21-22

Commander
U. S. Naval Air Ordnance Test Station
China Lake, California
copy 7

Dr. F. V. Hunt
Harvard University
Cambridge, Massachusetts
copy 23

Director, Marine Physical Laboratory
University of California
Scripps Institute of Oceanography
San Diego, California
copy 8

Director
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts
copy 24

Director
Bell Telephone Laboratories
Whippany, New Jersey
copies 9-10

Director
Lamont Geological Observatory
Torrey Cliff
Palisades, New York
copies 25-26

Committee on Undersea Warfare
Naval Research Council
National Academy of Sciences
2101 Constitution Avenue
Washington 25, D. C.
copies 11-12

Chief, Bureau of Aeronautics (AV-43)
Navy Department
Washington 25, D. C.
copies 27-28

Chief, Bureau of Ships (Code 688)
Navy Department
Washington 25, D. C.
copies 13-14

Chief, Bureau of Ordnance
Navy Department
Washington 25, D. C.
copies 29-30

The Hydrographer
U. S. Navy Hydrographic Office
Washington 25, D. C.
copies 15-16

Chief of Naval Operations
Navy Department
Washington 25, D. C.
 (Op-001) copy 31
 (Op-91) copies 32-33
 (Op-312) copies 34-35
 (Op-316) copies 36-37

Commanding Officer
ONR Branch Office
Navy No. 100
Fleet Post Office
New York, New York
copies 38-39

British Joint Services Mission
Main Navy Building, Room 4924
Washington 25, D. C.
via
Chief of Naval Operations (Op-316d)
Navy Department
Washington 25, D. C.
copies 40-42

Admiralty Research Laboratory
Teddington-Middlesex, England
via
Chief of Naval Operations (Op-316)
Navy Department
Washington 25, D. C.
copy 43

Commander
Armed Services Technical
 Information Agency
Arlington Hall Station
Arlington, Virginia
copies 44-53

Commander
Submarine Development Group II
U. S. Naval Submarine Base
Box 70
New London, Connecticut
copies 54-55

Weapons Systems Evaluation Group
Office of Sec'y of Defense
Room 2E1006- Pentagon Building
Washington 25, D. C.
copy 56

Commanding Officer
ONR Branch Office
346 Broadway
New York 13, New York
copy 57

Canadian Joint Staff
2450 Massachusetts Avenue, N.W.
Washington 25, D. C.
via
Chief of Naval Operations
(Op-316)
Navy Department
Washington 25, D. C.
copies 58-60

